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Treatment of Shale Gas Wastewater in the Marcellus: A Comparative Analysis

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by

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Treatment of Shale Gas Wastewater in the Marcellus: A Comparative Analysis

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This analysis focused primarily on three main treatment methods which were re-use, recycle, and disposal wells. The re-use treatment option is when wastewater is mixed with source water in order to meet fracturing water requirements. With this option, the hope is that the wastewater for re-use will require little or no treatment at all. The second treatment option is the recycle option. This option provides high quality water for re-use or discharge to the environment using a recycling technology. The credibility of this option is heavily dependent on its ability to recycle almost all of the wastewater with little or none left for disposal or treatment. The third option is well disposal. This entails disposing all of the wastewater into a deep formation.

The software used for building the model is called @Risk. The model's costs were estimates from recent research to capture the risks and uncertainties associated with wastewater disposal. The model revealed that re-use option remains the most cost effective treatment method to reduce overall water management cost in the Marcellus. The re-use option is most viable when a hydraulic fracturing schedule is continuous (no significant storage requirement) and infrastructure is available to transport wastewater from one fracturing operation to the other.

The recycle option is the second most viable disposal option. This option is most effective when the hydraulic fracturing schedule is staggered in both time and distance because distilled water from recycling facilities can be easily discharged into the environment or stored.

The most unfavorable option for wastewater management at the Marcellus is the well disposal option due to the high cost of trucking wastewater to disposal wells in neighboring states or counties. It also requires the highest usage of fresh water. A well disposal option can be favorable at the onset of a hydraulic fracturing schedule when there are low levels of infrastructure, hydraulic fracturing programs are not continuous or localized in proximity, and the volume of wastewater does not exceed the capacity for injection. In this case, disposal wells can be more favorable than recycle or re-use if they are in close proximity to drilling sites.

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Introduction

Shale gas is one of the fastest growing trends in the global oil and gas sector[1]. Technological advancement in exploration and production has enabled oil and gas companies to tap into resource plays that were once considered to be uneconomical[2]. The nature of this newly accessible resource is such that it will require extensive infrastructure for transportation and storage for it to meet demand requirements in different parts of the country[3]. Also as a result of this resource development, there is extensive need for investments to support the continuous production of natural gas from the different plays across the country. Some of which include Marcellus, Barnett, Eagle Ford, Woodford and Utica Shales. This research focuses mainly on the Marcellus Shale because it is one of the more contentious plays due to controversies surrounding the impact of production of natural gas on the environment. The debate of whether the resources of the Marcellus can be fully tapped without adverse impact on the environment is an ongoing controversy. Opponents of hydraulic fracturing believe that oil and gas companies will act solely in the interest of their shareholders at the expense of the sustainability of natural resources. Supporters of hydraulic fracturing on the other hand believe that the benefits accrued by exploiting the resources of the Marcellus far out weight the cost and that opponents of the new technology are using fear tactics and exaggeration to polarize the conversation[4].

Another component of concern for many is the reliability of current regulatory structures to deal with this development. Some concerned citizens and environmental groups have been vocal in expressing that shale gas operations have led to groundwater contamination in their communities. They seek tougher regulatory measures of shale gas production through the implementation of federal statues, Safe Drinking Water Act (SDWA) and Clean Water Act (CWA) in regulating all hydraulic fracturing operations within the country[5]. Various state regulatory agencies on other hand insist that a federal regulation is unnecessary because there is no proof of groundwater contamination from hydraulic fracturing operations which had been regulated by the states since the inception of hydraulic fracturing technology. As of 2011, the state of Pennsylvania has ordered all commercial and publicly owned water treatment utilities to stop accepting shale gas wastewater due to investigations that confirm that low levels of radioactive particles were found in streams (levels above safety standards)[6].

Another major issue is the subject of Market. The issue of price is closely tied to the subject of production and development[7]. If natural gas prices are in decline, exploration and production (E&P) companies are less likely to produce because it is not economical. The major difference between natural gas prices and crude oil prices is that crude oil is traded internationally because the commodity can be easily moved from one region of the world to another. Natural gas on the other hand cannot be easily transported from one region of the world to another due to its high combustive nature. Gas must be compressed and liquefied before it can be moved. This would require the construction of natural gas terminals to allow for the transportation of Liquefied Natural Gas (LNGs). Due to significant capital requirements to turn natural gas into LNG for transportation overseas, a majority of E&P companies source the services of commercial pipeline firms for transportation and storage of dry gas domestically to meet the needs of municipalities, cities, and states through sales to publicly and privately owned natural gas power plants. Geographical isolation of natural gas due to transportation constraints has led to more supply than demand domestically compared to crude oil which can be easily moved from one region of the world to another to meet demand requirements. Natural gas within the U.S is traded at Henry Hub in Southern Louisiana.

Why is the Marcellus Important?

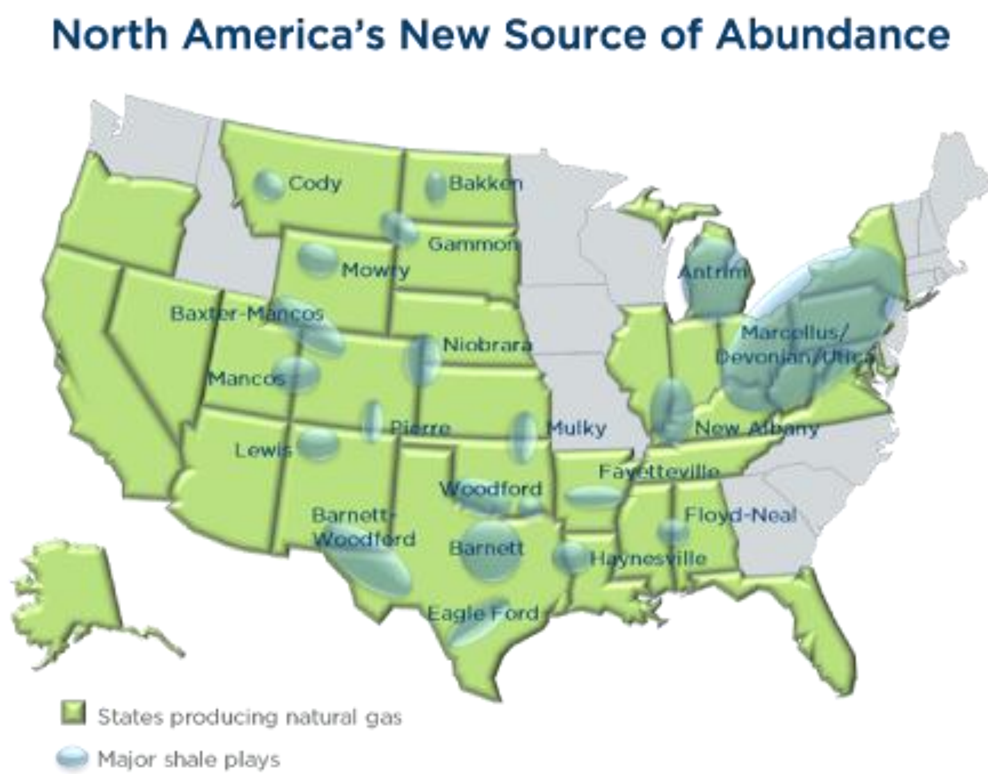
The span of the Marcellus shale ranges from Ohio in the west to Pennsylvania and New York in the North East to West Virginia in the South[8] (Figure 2). The most recent estimates by the Energy Information Administration (EIA) suggest that the play could contain about 141 trillion cubic feet[9] of natural gas revised from an earlier version of about 410 trillion cubic feet based on production information as a result of drilling in 2011[10]. These resources that were once considered uneconomical to drill due to the lack of adequate technology are now predicted to be the source of energy for the future. What makes the Marcellus even more important than the other shale gas plays across the country is its location. Location is an important factor in determining the ability of resources to meet demand requirements because it makes it easier and cheaper for producers to supply power plants and other end users but also and even more importantly, it provides the opportunity for producers to react quickly to demand changes and market prices fluctuations.

For example, the Marcellus Shale extends from the Finger Lakes region and Southern Tier of New York, eastern Ohio, northern and western Pennsylvania, western Maryland and through most of West Virginia. The shale in eastern Pennsylvania extends across the Delaware River into extreme western New Jersey[11]. Named as a result of a unique outcrop near the village of Marcellus in New York State, the formation extends throughout much of the Appalachian Basin. The shale mainly contains a vast amount of untapped natural gas and its geographic proximity to high-demand markets along the East Coast of the U.S makes it strategically important and attractive to energy development corporations. The Marcellus shale formation of the Appalachian basin represents the largest unconventional gas resource in the United States.

Conventional and Unconventional Reservoirs

Major shale gas basins exist throughout the United States. Figure 1 below shows the major shale basins in the United States. Unconventional shales are organic rich, fine grained sedimentary rocks. They are a source of and also serve as reservoirs for hydrocarbons[12]. In this case, the gas occupies the pore spaces and the gas is sorbed to the organic matter. The Society of Petroleum Engineers defines unconventional resources as “petroleum or gas accumulations that are pervasive throughout a large area and that are not significantly affected by hydrodynamic influences (they are also called continuous-type deposits)”[13]. Conventional petroleum and natural gas reserves on the other hand occur in porous sandstones and carbonate reservoirs[14]. Through buoyancy, the petroleum migrates upward from its organic source until an impermeable cap-rock (such as shale) traps it in the reservoir rock[15]. Shale can be as porous as other sedimentary reservoir rocks but their extremely small pore sizes make them relatively impermeable to gas flow unless natural or artificial fractures occur[16].

Figure 1: Major Shale Basins in the United State



Source: http://anga.us/why-natural-gas/abundant/shale-plays

Economic Challenges with Production and Development of Shale Formation

Oversupply remains a major factor that is driving down the price of natural gas[17]. By January of 2012, the price of natural gas had plunged below $3 as a result of over-production and break-even costs was between $4 to $6 as operators faced significant shortfalls[18]. Major shale gas producers in the U.S. include Chesapeake Energy Corporation, XTO Energy (ExxonMobil), Devon Energy, Encana, Southwestern Energy, and Newfield Exploration Company[19]. Low natural gas prices has created major setback in infrastructure development and resource exploitation[20].

The two major impediments to sustainable natural gas prices are high demand and transportation to market or (place of use). The shale gas revolution has created an abundant amount of resources in the United States. Due to the inability to easily transport natural gas across the world, there is no world market price. The forces of demand and supply within individual countries determine what the price of natural gas would be. In the U.S for example October 2013 natural gas prices are round $3.47/MMBtu[21] due to abundance of resources but low demand while in a country like Japan, Liquefied Natural Gas (LNG) prices can range from $13 to $16[22]. The depressed natural gas price in the U.S has prompted a company like Chesapeake that once focused on dry gas plays to acquire crude oil and liquid-rich assets that have enabled them to leverage their expertise from natural gas operations into the crude oil business. The similarity in extracting both commodities creates synergistic opportunities for companies to diversify their assets in a manner that reduces their exposure to the volatilities in natural gas prices (overall decline in prices). Natural gas prices have also been known to be subject to seasonality. In the wintertime, natural gas prices tend to increase due to a spike in demand and lack of adequate storage capacity (storage restraint mainly in the NE region) which is followed by a reduction in prices as the season comes to an end. Other factors that cause natural gas volatility is pipeline shortage to service certain growth markets and natural disasters. As indicated in Figure 3, based on 15 years historical prices from the New York Mercantile Exchange (NYMEX), there are clear indications of markets volatilities in natural gas prices as a result of unexpected events like hurricane Katrina in August of 2008. Trends and seasonality can also be extracted from the graph as it clearly shows that there was an upward trend in demand until around 2008 after prices began to decline due to excess supply and low demand (As a result of improved extraction technology – Hydraulic fracturing of Shale formation). The graph further indicates that year-to-year volatility after 2008 declined significantly due to the excessive supply of natural gas which exceeded domestic market demand. Seasonality can also be view on the graph as demand increases towards the end of every year and beginning of the following year but begins to decline as the spring season comes around the corner.

Geology and Natural Gas Potential of the Marcellus Shale

The Marcellus Shale is made of sedimentary rocks deposited over 350 million years ago during the middle-Devonian period. Geologic strata deposited in the Appalachian basin are likely to produce more gas than oil[23]. Oil production within this region is associated with younger Pennsylvanian age strata. A majority of this black, organic-rich shale lies beneath much of southern New York State, western and northeastern Pennsylvania, West Virginia, parts of Virginia and Maryland and eastern Ohio[24]. Its depth ranges from about 2,000 feet to 9,000 feet and its aerial extent is estimated as 95,000 square miles (Figure 4). The shale's non-uniform thickness varies from about 50 feet to 250 feet as indicated in (Figure 5).

Thicker shale with greater organic material yields more gas and are more economically desirable to produce. The amount of water produced in the Marcellus could vary across regions since shale formations typically produce much less water than traditional oil and gas fields or coalfields. Shale in northeast Pennsylvania and southeast New York State have characteristics to produce dry natural gas while shale in western Pennsylvania and New York produces wetter gas that contains petroleum liquids. Therefore, in the Marcellus Shale, the natural gas varies from wet in the western portion of Pennsylvania to dry in the northeastern part of Pennsylvania as shown in Figure 6. The deeper the formation the less likely it is to find petroleum liquids or oil as a result of high temperatures that change the chemistry within the organic material into gases. This is because the components that make up natural gas depend on the thermal maturity of the gas which is defined by how much temperature and pressure the geologic formation has experienced over time as shown in Figure 7. Therefore it is more likely that the more thermally mature region will consist of methane (dry gas) while the less thermally mature region will contain natural gas liquids which will include ethane, butane, propane, and pentane. Wet gas is currently considered to be more valuable than dry gas because in addition to methane, operators can get other compounds that can be sold separately on the market to generate more revenue. Due to higher margin on wet gas, some operators in the Marcellus will focus more activity in the southwest region of Pennsylvania and less in the northeast[25].

Natural Gas Supply and Demand in the Northeast Region

In 2012, the northeast region of the U.S alone consumed about 5 tcf of natural gas[26]. New York State had a consumption of about 1.2 tcf as indicated in Figure 8 which represented the largest natural gas consumption in the region. The U.S as a whole consumed about 25 tcf in 2012[27]. Reserves at the Marcellus are estimated to be about 141 tcf[28] of which about 84 tcf is technically recoverable a revision from 2002 estimates of 2 tcf[29]. In this sense, assuming that all the resources at the Marcellus is used within the region; it would only take about 17 years to run out of resources at the Marcellus. This being said, better technology and recovery methods might extend the supply of natural gas from these formations.

Transportation of Natural Gas

As many as 20 interstate natural gas transmission pipelines currently serve the northeast region of the United States (Figure 9). These systems of pipelines deliver natural gas to various intrastate natural gas pipelines and at least 50 local distribution companies in the region. Several long distance natural gas pipelines supply the region as well in addition to the natural gas produced within the region. Natural gas is supplied from the southeast into Virginia and West Virginia, and from the Midwest into West Virginia and Pennsylvania[30]. Imports from Canada come into the region through New York, New Hampshire, and Maine. Liquefied Natural Gas (LNG) comes into the region through import terminals located in Canada, New Brunswick, Maryland, and Massachusetts[31].

The eastern portion of the Marcellus Shale produces natural gas that is of high enough quality that it requires little or no treatment for injection into transmission pipelines because it is dry gas as a consequence of the formation's characteristics. Any increased shale gas production from New York and parts of Pennsylvania will be met by the Millennium Pipeline project in southern New York State which would further serve the natural gas needs of the region[32]. However, the topography in West Virginia possesses a challenge to developing additional pipeline capacity and other support infrastructure. An extensive network of gathering pipelines will be needed to bring the gas out of the well fields[33].

Groundwater Resource Challenges – Laws and Regulations

Drilling activities and fracturing fluid disposal from hydraulic fracturing treatments due to stimulation of gas production from shales have stirred environmental concerns over perceived excessive water consumption, drinking water well contamination, and surface water contamination. There are significant environmental management challenges in the Marcellus region as a result of wastewater pumped back to the surface after the fracturing process. The wastewater contains high content of total dissolved solids (TDS) and other contaminants which must be disposed of or properly treated before discharge to surface waters. Two major federal laws regulate wastewater in the United States. The Safe Drinking Water Act (SDWA) regulates deep well injection of such wastewater while the federal Clean Water Act and respective state laws regulate the discharge of wastewater water and other drilling wastewater to surface waters[34]. Hydraulically fractured wells are regulated by the states. Historically, the EPA has not regulated hydraulic fracturing due to the fact that it is not classified as an act of underground well injection, and the 2005 Energy Policy Act exempted hydraulic fracturing from SDWA regulation[35]. Future legislation could potentially make hydraulic fracturing subject to regulation under SDWA, increasing federal oversight of drilling on both state and federal lands across the country. An example of groundwater oversight and management is the Susquehanna River Basin Commission (SRBC) in Pennsylvania which overseas implementation of water withdrawals from the Susquehanna Basin[36]. The commission is a federal-interstate compact created by the Susquehanna River Basin Compact between New York State, Pennsylvania, and Maryland[37]. In

2012, protests emerged in these areas over the license that was given to hydraulic fracturing operators to draw water from the Basin[38].

2

Water Resource Concerns in the Marcellus Shale Area

The Marcellus Shale development is subject to regulation under various state and federal laws. A large volume of water is needed to drill and hydraulically fracture the shale, and the disposal of this water and other wastewater associated with gas extraction may trigger regulatory attention due to significant water quality and quantity challenges and issues. The U.S. Geological Survey stated in its publication, "Concerns about the availability of water supplies needed for gas production, and questions about wastewater disposal have been raised by water-resource agencies and citizens through the Marcellus Shale gas development region"[39].

Hydraulic fracture process is a water-intensive practice which involves injecting water, sand, and chemicals into the shale layer at extremely high pressures to release the trapped natural gas. Typical projects use 1 to 3 million gallons of water for each well but large projects may require up to 5 million gallons of water. A smaller natural gas well in the Barnett Shale uses an estimated 3.5 or more million gallons of water for its fracturing operations[40]. With regards to the Marcellus Shale, the USGS states that "many regional and local water management agencies are concerned about where such large volumes of water will be obtained and what the possible consequences might be for local water supplies"[41]. The question of water availability for fracturing purposes is also an important subject of discussion and research but will not be covered in this thesis. Reports show that a horizontal Marcellus well could require about 3 to 8 million gallons of water within a period of a week[42]. In Pennsylvania, the gas industry drilled about 1,386 Marcellus wells in 2010 compared to 763 in 2009[43]. Reports also indicate that about 10 percent of the injected fluid resurfaces as wastewater in the subsequent 30 days resulting to about 300,000 to 800,000 gallons of wastewater per drilled well[44]. In the second half of 2010 alone, the industry produced about 235 million gallons of wastewater (7.4 million barrels)[45].

Wastewater Disposal Methods and Challenges

During a hydraulic fracturing process, some of the injected fluids remain trapped underground while fluids recovered could range from 10 to 80 percent of the volume injected depending on formation characteristic. USGS states that the additives in a three million gallon fracturing process could yield about 20,000 gallons of chemicals because the quantity of fluid used is so large. The well service company may temporarily retain the wastewater and brine in a line retention pond or in open-air before reusing it or disposing it. Reclamation must be done on the temporary storage pits when the drilling and fracturing operations end. The well operator will then treat, separate, and dispose the natural brine co-produced with gas.

Underground Injection

Underground injection can be used to dispose of the wastewater that is co-produced with the natural gas. Underground injection is used in the oil and gas industry in some western states, southern states and in Ohio. The industry is yet to use underground injection as a disposal alternative for gas production in eastern Marcellus Shale where the play is at its deepest.

Challenges for underground Injection at the Marcellus

(a) Lack of suitable injection zones within drilling proximity

(b) Permeable Cambrian sandstones that lie beneath the Marcellus seems probable as an injection zone – Pennsylvania currently has 7 brine disposal wells of which only 1 is a commercial well and is currently not permitted for Marcellus wastewater disposal. New York State has 6 brine disposal wells while West Virginia has 74 and Ohio has 159 brine disposal wells

(c) Cambrian Mt. Simon sandstone in Ohio considered most suitable but is relatively far from well sites in Pennsylvania and New York

(d) Non-quantitative assessments like public perception should also be evaluated when considering this option as a result of the footprints of the wastewater hauling trucks to the injection sites

Publicly Owned Treatment Works or Industrial Treatment Facility

Regulations established by the states under Section 303 of the Clean Water Act (CWA) protect designated beneficial uses of surface waters, such as public water supply or water meant for recreation. If the wastewater contains contaminants that prevent discharge to surface water without further treatment, the well service operator will have to transfer the wastewater off-site to an industrial treatment facility or a municipal sewage treatment plant that is capable of handling and processing the wastewater. In this case, the operator of the publicly owned treatment works (POTW) or industrial treatment facility would assume responsibility for treating the waste before discharging it into nearby receiving water in compliance with limits contained in the facility's discharge permit.

Challenges for POTW at the Marcellus

(a) Proximity to well site – This is major challenge for the off-site option because the cost of transporting wastewater from the well site to the fixed facility can make the process uneconomical. In Pennsylvania, there are five facilities that have been licensed by the state to treat shale gas wastewater but unfortunately most of the well sites are located in northeast Pennsylvania while the closes facility is 250 miles away

(b) Re-engineering POTW to process wastewater might not be economically feasible since they were initially built to handle other forms of waste

(c) Availability of power – Providing a fixed facility for wastewater treatment requires electricity to run the treatment plant but most well sites are located in remote areas where electricity transmission lines are not available

(d) Some well sites do not produce enough wastewater to justify the construction of a fixed facility

On-site treatment (Re-use/Recycling)

On-site treatment and reuse is currently a subject of discussion by many professionals and academics in the industry because it provides the opportunity for oil and gas companies to reuse or recycle wastewater which would reduce competition for local water supply in municipalities where oil and gas companies operate. Companies are considering options such as advanced oxidation and membrane filtration processes. Recycle technologies may be capable of recovering about 70% to 80% of the initial water to portable water standards which makes the water available for re-use. The remaining 20% to 30% will be considered brine water which could be further processed to be used for fracturing purposes or sent off-site for treatment and disposal.

Challenges for on-site treatment (Re-use/Recycle)

(a) Capital Intensive – The on-site treatment option is not a cheap option. A lot of the technologies used by companies that are providing these services are patented to protect their intellectual property due to extensive Research and Development (R&D) costs associated with on-site wastewater purification technologies.

(b) Portable water content ratio – One major criterion to justify the high cost of an on-site purification technology is portable water ratio to brine after purification. This measures the efficiency of the technology. Since the justification for the recycle technology is the ability to convert wastewater into portable water, the question then becomes how much portable water one can get from a certain quantity of wastewater. An example of a successful implementation of this technology is in the Barnett Shale with Fountain Quail Water Management Technology. With the use of an on-site commercial mobile unit technology, the recycling process allows for reuse of about 80 percent of wastewater while the remaining 20 percent (brine) is sent for disposal using underground injection. As of October 2010, the mobile technology has processed about 12.7 million barrels of wastewater to recover over 9.9 million barrels of reusable portable water.

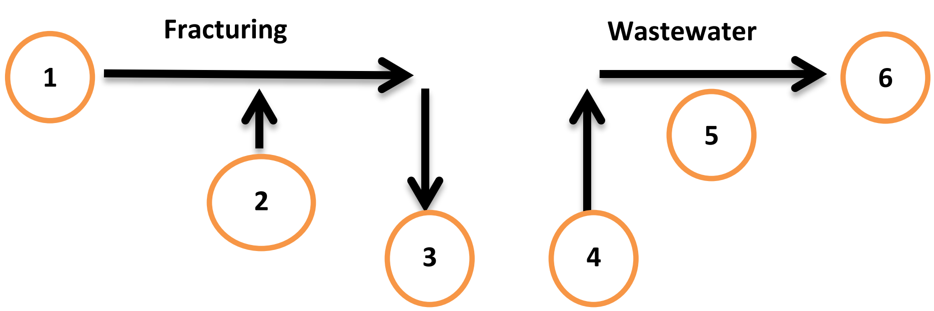
(c) Mobility of Technology – These technologies must be able to reach the well sites therefore it is loaded on the back of huge trucks and transported to various locations. The footprints of these huge trucks could create extra work for the oil and gas operating companies

(d) Equipment used for wastewater purification deteriorates due to the corrosive nature of the chemical elements in shale gas wastewater

3

Wastewater Composition Analysis

Finding the appropriate treatment option is dependent on understanding the quality and quantity of the hydraulic fracturing wastewater. There are six important variables that influence the chemistry of wastewater. These variables include 1) The source water chemistry 2) Drilling and hydraulic fracturing program 3) Formation geochemistry and rock mechanics 4) communication with water bearing formations 5) Blending on surface with other waters 6) Time on surface. Diagram A below illustrates the different variables that influence the wastewater's quantity and quality[46].



1) Source water chemistry

2) Drilling and hydraulic fracturing program

3) Formation geochemistry and rock mechanics

4) Communication with water bearing formations

5) Blending on surface with other waters

6) Time on surface

Diagram A: Variables that Influence Wastewater Quality and Quantity

Source Water Chemistry

The major challenge for source water as a composition of fracturing fluid is the potential for incompatibility between the source water and the fracturing fluid composition which could eventually lead to scaling. Scaling is a situation that occurs when dissolved mineral salts in water precipitates and forms solid deposits[47]. Key concern for shale gas fracturing fluid is the potential for barium sulfate scale formation[48].

Drilling and Hydraulic Fracturing Program

There are three major types of hydraulic fracturing namely:

1) Slick fracturing: Volume of a slick fracturing typically ranges between 2,520,000 to 3,780,000 gallons per fracturing[49]. Major composition of slick fracturing is primarily water with the combination of a propping agent, friction reducer, scale inhibitors, friction reducer, biocides, and surfactants.
2) Gel fracturing: Volume of a Gel fracturing is typically less than slick fracturing even though it contains more chemicals. The primary composition of a Gel fracturing is a water-based or cross-linked gel system which helps to increase the viscosity of the composition to improve the movements of the proppant.
3) Hybrid fracturing: This is a composition that is primarily a combination of a slick fracturing and a Gel fracturing.

The major challenge that fracturing fluid composition faces is the constant changes in fracturing technology which can require the compositions of a fracturing fluid to change.

Formation Geochemistry and Rock Mechanics

"Shale" is primarily a composition of calcite, clay, and quartz. Pore spaces within a shale formation will contain salt water and other organic materials like natural gas. The quality and quantity of the composition within a geologic formation are greatly influenced by factors such as time (how long the fluid has been underground), temperature, and the pH level all of which will determine the quality and quantity of the wastewater[50].

Communication with water bearing formations

Salt water bearing formations is another variable that can greatly influence the quality and quantity of a wastewater. Since shale formations often have overlying or underlying water-bearing formations, any communication between the producing zone and the water-bearing formation can result in larger volumes of produced water and high levels of salinity of wastewater composition[51].

Blending on surface with other waters

The wastewater that is returned to the surface is usually blended with other wastewater, produced water, or fracturing fluids. If the blending is not properly done, the new composition can delay further fracturing if the current fracturing technology cannot adapt to the new composition[52].

Surface Storage Time

Wastewater that is returned to the surface contains bacteria, fracturing chemicals, and naturally occurring materials from the formation. Bacteria have the potential to break down the organic materials which could lead to the production of hydrogen sulfide with the potential of creating corrosion and other safety concerns.

Economic Factors Affecting Disposal Strategy

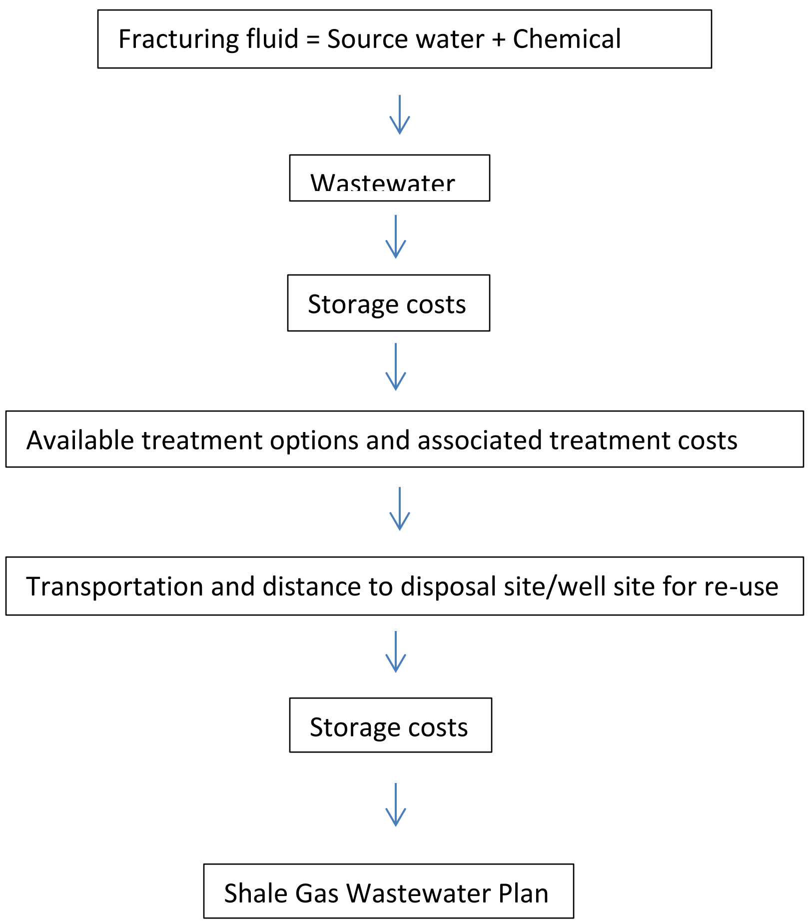


Diagram B: Factors and Costs that Influence Disposal Options

The above flowchart shows the different factors and costs an operator will consider before making a decision about a disposal option. Other factors that can affect a disposal strategy beyond the above listed factors are state and federal regulations, regional topography and infrastructure, fuel prices, and overall industry practice. Water management costs make up about 5 percent to 15 percent of drilling and completion costs[53], therefore minimizing the above costs will help an operator increase long-term profitability.

Wastewater Composition

One of the major challenges with wastewater is the high levels of TDS. The salinity and/or TDS in the wastewater are key components in evaluating a disposal strategy. TDS is a measure of dissolved matter (salts, organic matter, minerals etc.) in water[54]. The major compositions of TDS in the Marcellus include sodium, chloride, and calcium as shown in the table below. Flow back analysis from various U.S shale plays is shown below[55].

			SHALE PLAY					
COMPONENT			BARNETT	EAGLEFORD	FAYETTEVILLE	HAYNESVILLE	MARCELLUS	BAKKEN
Sodium	Na	(mg/L)	10,741	10,900	13,804	34,879	24,445	45,100
Potassium	K	(mg/L)	484	192	256	735	190	3,550
Magnesium	Mg	(mg/L)	316	111	293	828	263	720
Calcium	Ca	(mg/L)	2,916	1,270	1,046	7,052	2,921	9,020
Strontium	Sr	(mg/L)	505	203	267	1,354	347	
Barium	Ba	(mg/L)	15	10	18	1,121	679	13
Iron	Fe	(mg/L)	28	112	0	147	26	77
Chloride	Cl	(mg/L)	23,797	19,318	23,856	71,143	43,578	91,300
Sulphate	SO4	(mg/L)	309	163	13	-	4	440
Bicarbonate	HCO3	(mg/L)	405	736	6,161	382	261	126
Total Dissolved Solids	TDS	(mg/L)	39,516	33,015	45,715	117,641	72,714	150,346
Total Suspended Solids	TSS	(mg/L)	1272	840	700	868		

Diagram C: TDS Characterization

Different regions within a formation can have different levels of TDS. The level of the TDS will impact how much of the wastewater can be blended with fresh water for reuse. Areas with low levels of wastewater and low TDS are more likely to meet fracturing-water chemistry requirement enabling a significant portion of the wastewater to be reused with minimal treatment while areas with high levels of wastewater and high TDS will result in limited amount of wastewater that can be blended with fresh water and reused and will most likely require higher levels of treatment to meet fracturing-water chemistry requirements. Wastewater composition is one of the major determinants in a wastewater management strategy. Differences in composition can impact a disposal strategic options which could include treatability, disposal injectivity, and even variability of early and late-stage wastewater.

Water with high levels of suspended solids is more difficult to dispose without treatment because of a possible decrease in injectivity. This could limit the treatment options for a wastewater. Wastewater composition can vary from early-stage (1 to 5 days) to late-stage (10 to 30 days)[56]. Early stage wastewater typically has higher flow rate with lower TDS while late-stage wastewater has lower flow rate but higher TDS. To get a good estimate of average wastewater composition, it is important to consider TDS and wastewater volume jointly as a function of time. The graph below shows the inverse relationship between wastewater volume and TDS.

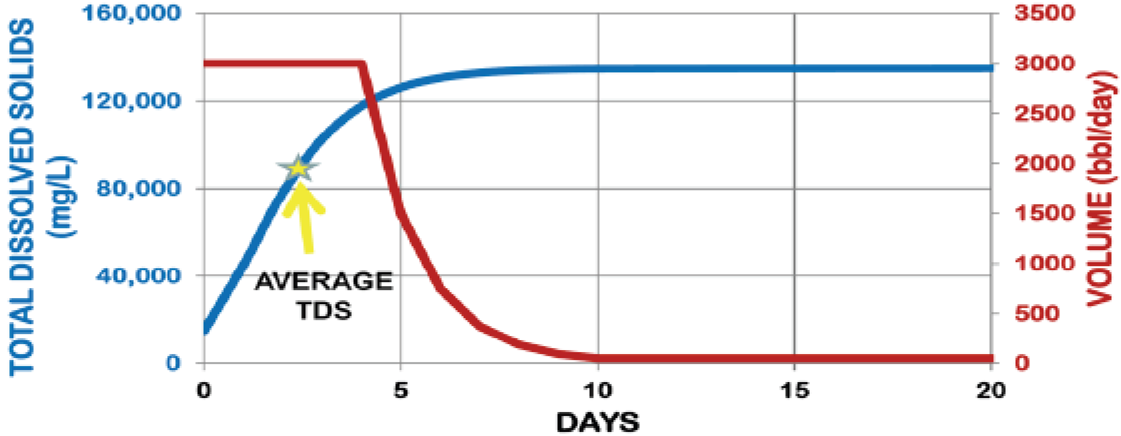


Diagram D: Wastewater volume vs. TDS[57]

Economic Analysis

This economic analysis will focus on three main methods of wastewater treatment which are recycling, re-use, and disposal wells. Since the state of Pennsylvania has stopped all utility facilities that were once disposing of treated shale gas wastewater to stop accepting these wastewaters, [58]the analysis of the various treatment methods will focus on recycling, re-use, and disposal wells.

Disposal Wells

The cost of a typical class II disposal well could range from $0.75/bbl to $3.00/bbl at the well[59]. Since disposal wells are practically non-existent in Pennsylvania and wastewater must be trucked to Ohio or West Virginia, this disposal option will require significant transportation cost.

Trucking and transfer pipelines are both viable transportation options. Trucking involves the use of water hauler typically hauling about 100 – 160 barrel of water per load. Trucking cost could range from \$0.02 to \$0.04/bbl/mile[60].

Re-Use Option

The re-use option provides the opportunity to mix the flow back with source water in order to meet the fracturing water requirements. Removal of Total Suspended Solids (TSS) might be necessary before the wastewater is adequate for re-sue. The level of treatment using a re-use option is heavily dependent on the chemistry of the flow back. Re-use technology typically ranges from \$1.00/bbl for basic TSS removal to over \$2.00/bbl if it warrants the removal of scale-forming components or particle-size polishing[61]. An overview of a re-use strategy is illustrated in diagram E below.

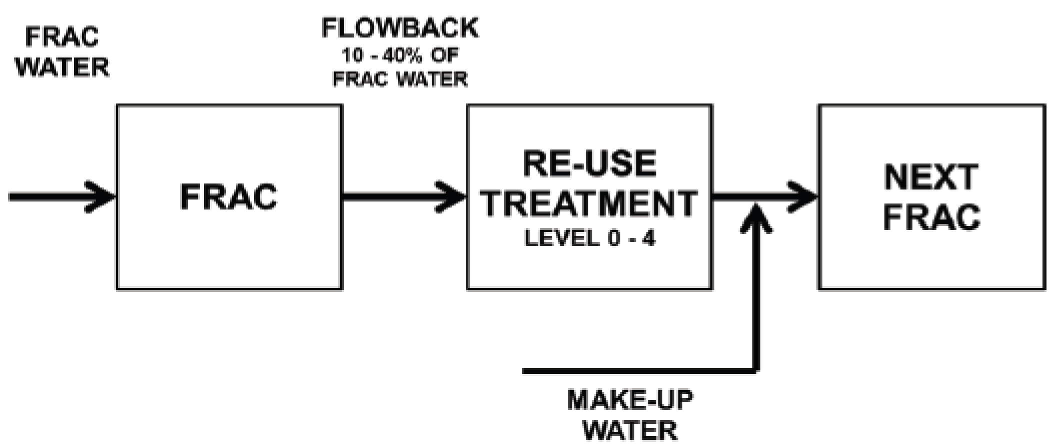


Diagram E: Re-use Strategy

Recycle Option

Recycling technology is used to remove suspended and dissolved material from water which provides high quality water for re-use or discharge to the environment. It provides the best quality of water which reduces environmental liabilities that could be associated with transportation or storage. Recycled water can also be used for other forms of industrial processes like irrigation. Since recycling reduces the amount of water meant for disposal, it decreases water management costs associated with disposal and transportation since it is charged volumetrically. An example of a recycling strategy is shown in diagram F below.

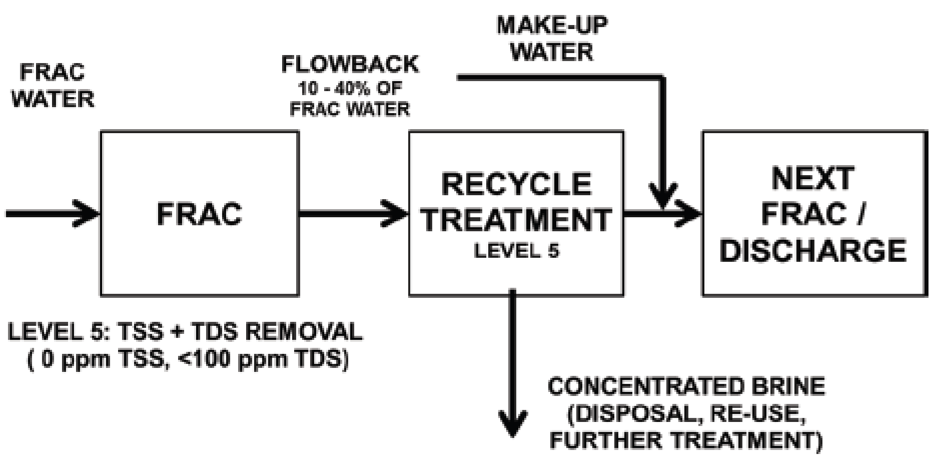


Diagram F: Recycling Strategy

An example of a recycling technology is Fountain Quail's NOMAD Technology which converts wastewater waters with high levels of salinity into distilled water[62]. The cost of a typical recycling technology can range from $3.50/bbl to $6.25/bbl[63].

4

Model Results and Conclusion

I built a model using @risk and various cost estimates from recently published research. The findings in this model suggest that re-use option is the most valuable as long as recovery for re-sue is above 50%. The recycle option is also viable as long as the disposal volume from the wastewater is at a minimum. As the disposal volume of the recycle option increases, it becomes a less favorable option as a result of the volumetric costs associated with trucking and injection. The disposal option is the least favorable option mainly due to transportation costs but becomes favorable when disposal wells are closer to well sites. Below is a breakdown of the model : The major components of this model are: (1) Fresh Water Supply Cost (2) Fresh Water Transportation Cost (3) Treatment Cost (4) Treated Water Transportation Cost (5) Disposal Transportation Cost (6) Disposal (Injection Cost).

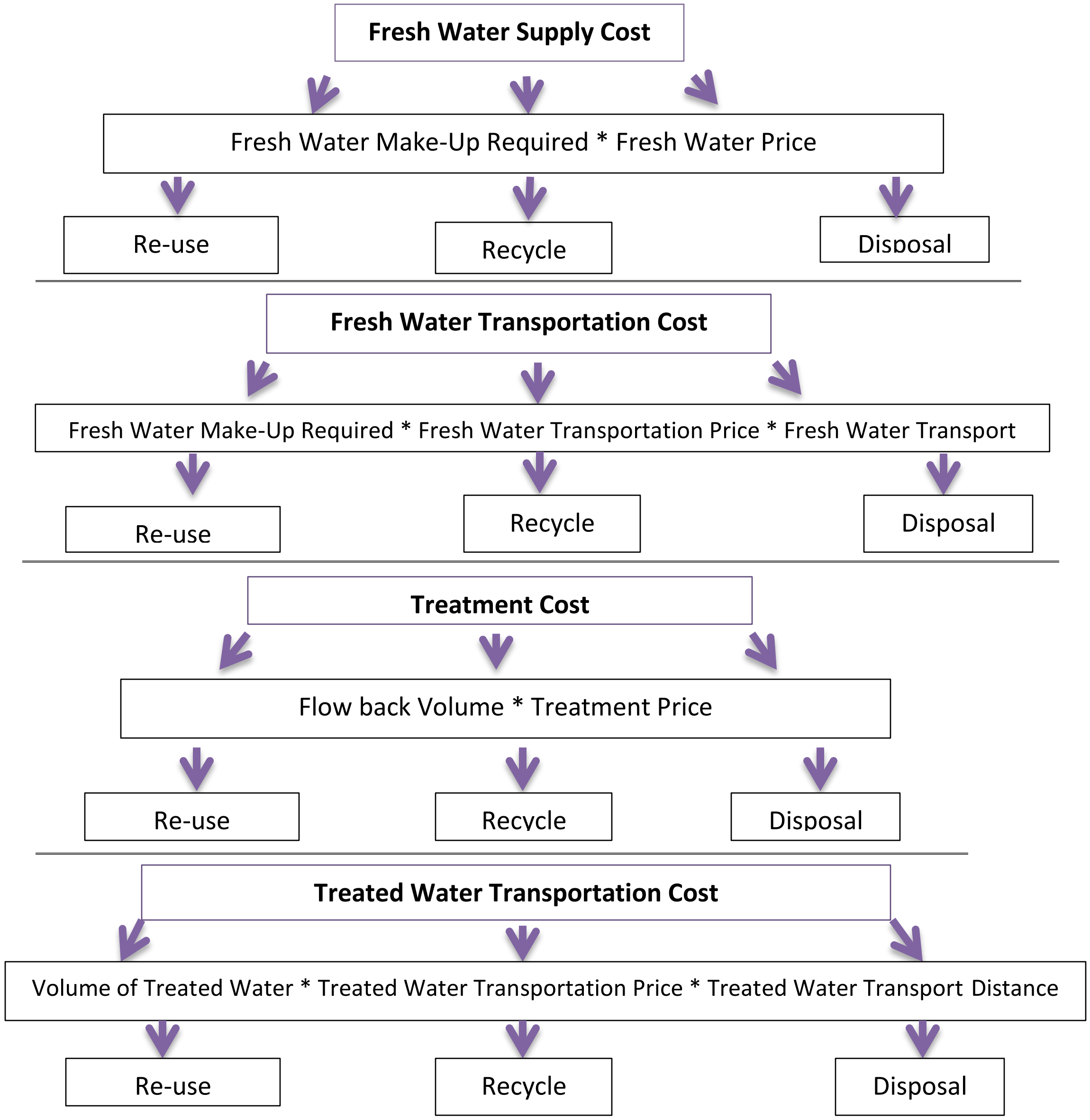


Diagram G: Waste Water Management Cost Flow Chart

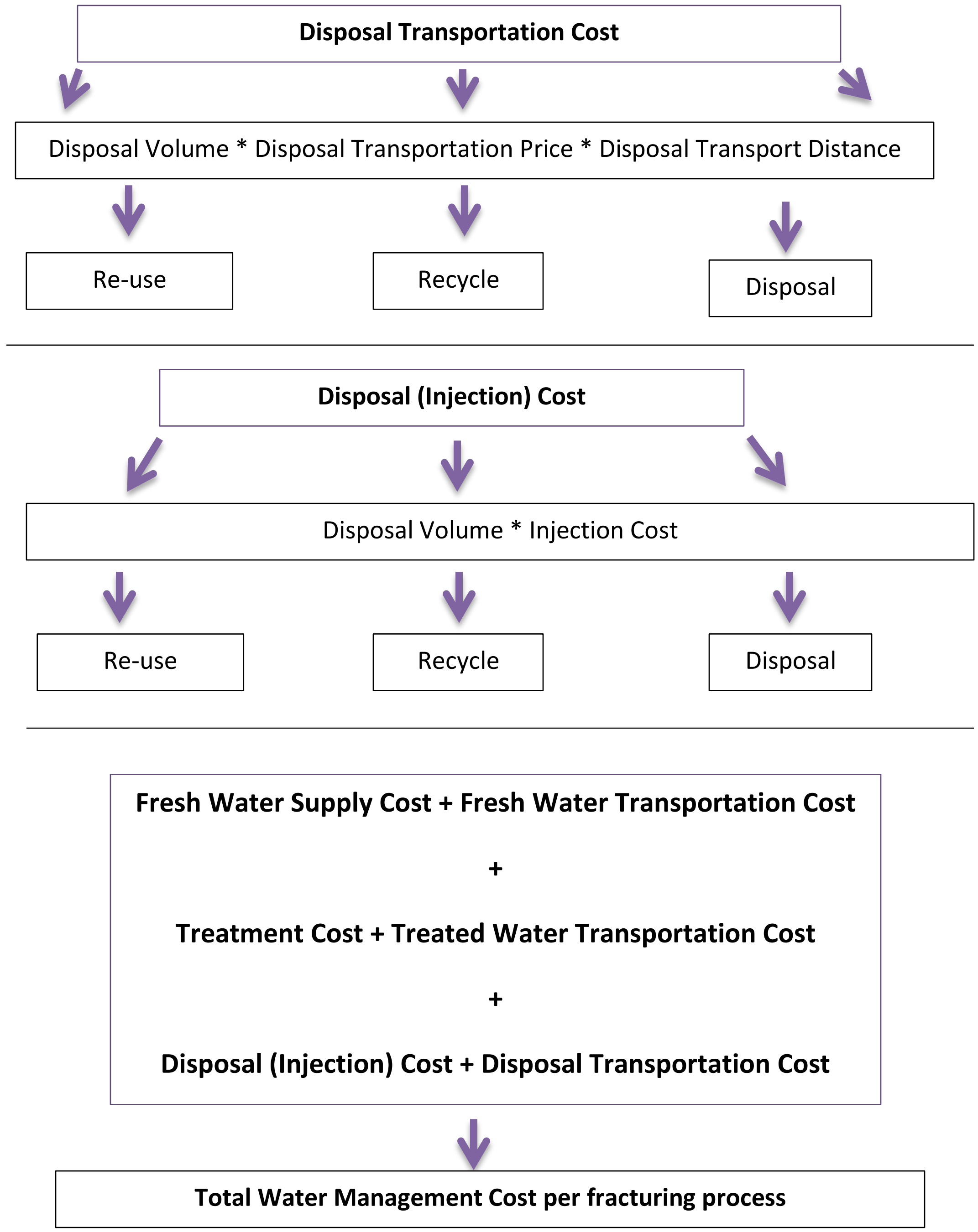


Diagram G Continuation

The model discussed is applicable to any geologic formation or region where the above treatment options are available. It provides the operator with the ability to customize the values that go into the model to suit their respective needs. The assumptions I made in building the model are as follows:

(1) Wastewater is 25% of total volume of injected fluid for hydraulic fracturing

(2) Average flow back TDS will be 120 barrels of total wastewater volume

(3) 100 percent of wastewater will be applicable for re-use when using the re-use option as illustrated in Table 1

(4) 62 percent of wastewater is recovered when using the recycle option as illustrated in Table 1

(5) Average flow back TDS of 120 barrels will be added to the 62 percent of wastewater to get the total treated water for re-use after recycle. The volume that will be disposed (using underground injection) after the recycle process is the difference between the total wastewater volume and total treated water for re-use after recycle. To reduce costs associated with injection, the percentage of recovery for re-use after recycle must be increased which minimizes the need for injection.

(6) The recovery for re-use using the re-use option is set at 100 percent which means that nothing will be sent for disposal using underground injection. If the recovery for re-use is reduced to 47 percent (meaning that 100% - 47% will be sent for underground

injection), the total cost for the re-use option and the cost of the recycle option becomes the same using this model as illustrated in Table 3.

(7) The assumption made in this model are such that maximizing recovery for re-use and minimizing the need for disposal using underground injection are the two major drivers. Increasing recovery for re-use reduces cost while an increase in the need for underground injection will increase cost.

(8) Cost, price, distance, percentage and volume estimates in this model are relative values adapted from research on operator cost estimates around the Marcellus. The assumption is that every operator will use whatever contractor they want and will be charged whatever cost is agreed upon which could be different from the values in this model.

(9) The purpose of the flexibility built in the model using @risk is to enable an operator or an analyst to use the model to build different uncertainties into the model. The @risk software has different distributions but for this model I used a risk triangle. A risk triangle is a distribution that uses a high, medium, and low measure to calculate an average for the distribution. For example, if the cost of fuel is projected to increase over the next year. The operator can go into the model to set the next year cost estimates using the three levels. The triangular distribution calculates an average of the three values as the most probable value. This enables the operator or analysts to periodically change the different levels to suit various uncertainties or preferences.

Table 1

Initial Model: Recovery for re-use = 100%, Recovery for re-use (recycle) = 62%

Frac Volume	(bbl)	120000			
Average flowback TDS	(mg/L)	80	Equivalence	(bbl)	120
Flowback (% of frac fluid)	(%)	0.25			
Fresh water Price	($/bbl)	0.15			
Fresh water Transportation Cost	($/bbl/mile)	0.02			
Fresh water Transportation Distance	(miles)	10			
Flowback Transportation Cost	($/bbl/mile)	0.04			
Treated Water Transportation Price, Re-Use	($)	0.04			
Treated Water Transportation Price, Recycle	($)	0.02			
Re-use Treatment Price	($/bbl)	1			
Recycle Treatment Price	($/bbl)	3.5			
Re-use, Recovery for Re-Use	(%) 100%	1			
Recycle, Recovery for Re-Use	(%)	0.62			
Average Distance of Re-Use facilities to frac	(miles)	10			
Average Distance of Recycle facilities to frac	(miles)	50			
Average Distance to disposal	(miles)	450			
Disposal (injection) cost	($/bbl)	1			
		DISPOSAL	**RE-USE**	**RECYCLE**	
Total Frac Fluid Volume	(bbl)	120,000	120,000	120,000	
Treated Water for Re-Use	(bbl)	-	30,000	18,720	
Fresh Water Make-Up Required	(bbl)	120,000	90,000	101,280	
Fresh Water Price	($/bbl)	0.15	0.15	0.15	
FRESH WATER SUPPLY COST	**($)**	**18,000**	**13,500**	**15,192**	
Fresh Water Make-Up Required	(bbl)	120,000	90,000	101,280	
Fresh Water Transportation Price	($/bbl/mile)	0.02	0.02	0.02	
Fresh Water Transportation Distance	(miles)	10	10	10	
FRESH WATER TRANSPORTATION COST	**($)**	**24,000**	**18,000**	**20,256**	
Flowback Volume	(bbl)	30,000	30,000	30,000	
Treatment Price	($/bbl)	-	1	3.5	
TREATMENT COST	**($)**	**-**	**30,000**	**105,000**	
Volume of Treated Water	(bbl)	-	30,000	18,720	
Treated Water Transportation Price	($/bbl/mile)	-	0.04	0.02	
Treated Water Transportation Distance	(miles)	-	10	50	
TREATED WATER TRANSPORTATION COST	**($)**	**-**	**12,000**	**18,720**	
Disposal Volume	(bbl)	30,000	-	11,280	
Disposal Transportation Price	($/bbl/mile)	0.04	0.04	0.04	
Disposal Transportation Distance	(miles)	450	450	450	
DISPOSAL TRANSPORTATION COST	**($)**	**540,000**	**-**	**203,040**	
Disposal Volume	(bbl)	30,000	-	11,280	
Injection Costs	($/bbl)	1	1	1	
DISPOSAL (INJECTION COST)	**($)**	**30,000**	**-**	**11,280**	
TOTAL WATER MANAGEMENT COST PER FRAC	**($)**	**612,000**	**73,500**	**373,488**	
			88%	**39%**	

Table 2: Formulas

Frac Volume	(bbl)	**=RiskTriang(100000,120000,140000)**			
Average flowback TDS	(mg/L)	**=RiskTriang(60,80,100)**	Equivalence	(bbl)	**=RiskTriang(100,120,140)**
Flowback (% of frac fluid)	(%)	**=RiskTriang(0.2,0.25,0.3)**			
Fresh water Price	($/bbl)	**=RiskTriang(0.12,0.15,0.18)**			
Fresh water Transportation Cost	($/bbl/mile)	**=RiskTriang(0.01,0.02,0.03)**			
Fresh water Transportation Distance	(miles)	**=RiskTriang(5,10,15)**			
Flowback Transportation Cost	($/bbl/mile)	**=RiskTriang(0.03,0.04,0.05)**			
Treated Water Transportation Price, Re-Use	($)	**=RiskTriang(0.02,0.04,0.06)**			
Treated Water Transportation Price, Recycle	($)	**=RiskTriang(0.01,0.02,0.03)**			
Re-use Treatment Price	($/bbl)	**=RiskTriang(0.5,1,1.5)**			
Recycle Treatment Price	($/bbl)	**=RiskTriang(3,3.5,4)**			
Re-use, Recovery for Re-Use	(%) 100%	**1**			
Recycle, Recovery for Re-Use	(%)	**=RiskTriang(0.6,0.62,0.64)**			
Average Distance of Re-Use facilities to frac	(miles)	**=RiskTriang(5,10,15)**			
Average Distance of Recycle facilities to frac	(miles)	**=RiskTriang(40,50,60)**			
Average Distance to disposal	(miles)	**=RiskTriang(250,500,600)**			
Disposal (injection) cost	($/bbl)	**=RiskTriang(0.75,1,1.25)**			
		DISPOSAL	**RE-USE**	**RECYCLE**	
Total Frac Fluid Volume	(bbl)	=C1	=C1	=C1	
Treated Water for Re-Use	(bbl)	-	=C3*C1*C12	=C3*C1*C13+F2	
Fresh Water Make-Up Required	(bbl)	=C19	=D19-D20	=E19-E20	
Fresh Water Price	($/bbl)	=C4	=C4	=C4	
FRESH WATER SUPPLY COST	**($)**	**=C21*C22**	**=D21*D22**	**=E21*E22**	
Fresh Water Make-Up Required	(bbl)	=C21	=D21	=E21	
Fresh Water Transportation Price	($/bbl/mile)	=C5	=C5	=C5	
Fresh Water Transportation Distance	(miles)	=C6	=C6	=C6	
FRESH WATER TRANSPORTATION COST	**($)**	**=C25*C26*C27**	**=D25*D26*D27**	**=E25*E26*E27**	
Flowback Volume	(bbl)	=C3*C1	=C30	=C30	
Treatment Price	($/bbl)	-	=C10	=C11	
TREATMENT COST	**($)**	**-**	**=D30*D31**	**=E30*E31**	
Volume of Treated Water	(bbl)	-	=D20	=E20	
Treated Water Transportation Price	($/bbl/mile)	-	=C8	=C9	
Treated Water Transportation Distance	(miles)	-	=C14	=C15	
TREATED WATER TRANSPORTATION COST	**($)**	**-**	**=D34*D35*D36**	**=E34*E35*E36**	
Disposal Volume	(bbl)	=C30	=D30-D34	=E30-E34	
Disposal Transportation Price	($/bbl/mile)	=C7	=C40	=C40	
Disposal Transportation Distance	(miles)	=C16	=C41	=C41	
DISPOSAL TRANSPORTATION COST	**($)**	**=C39*C40*C41**	**=D39*D40*D41**	**=E39*E40*E41**	
Disposal Volume	(bbl)	=C39	=D39	=E39	
Injection Costs	($/bbl)	=C17	=C45	=C45	
DISPOSAL (INJECTION COST)	**($)**	**=C44*C45**	**=D44*D45**	**=E44*E45**	
TOTAL WATER MANAGEMENT COST PER FRAC	**($)**	**=C23+C28+C42+C46**	**=D23+D28+D32+D37+D42+D46**	**=E23+E28+E32+E37+E42+E46**	
			=(C47-D47)/C47	**=(C47-E47)/C47**	

Table 3

Changed Model: Recovery for re-use = 47%, Recovery for re-use = 62%

Frac Volume	(bbl)	**120,000**			
Average flowback TDS	(mg/L)	**80**	Equivalence	(bbl)	**120**
Flowback (% of frac fluid)	(%)	**0.25**			
Fresh water Price	($/bbl)	**0.15**			
Fresh water Transportation Cost	($/bbl/mile)	**0.02**			
Fresh water Transportation Distance	(miles)	**10**			
Flowback Transportation Cost	($/bbl/mile)	**0.04**			
Treated Water Transportation Price, Re-Use	($)	**0.04**			
Treated Water Transportation Price, Recycle	($)	**0.02**			
Re-use Treatment Price	($/bbl)	**1**			
Recycle Treatment Price	($/bbl)	**3.5**			
Re-use, Recovery for Re-Use	(%) 47%	**0.47**			
Recycle, Recovery for Re-Use	(%) 62%	**0.62**			
Average Distance of Re-Use facilities to frac	(miles)	**10**			
Average Distance of Recycle facilities to frac	(miles)	**50**			
Average Distance to disposal	(miles)	**450**			
Disposal (injection) cost	($/bbl)	**1**			
		DISPOSAL	**RE-USE**	**RECYCLE**	
Total Frac Fluid Volume	(bbl)	120,000	120,000	120,000	
Treated Water for Re-Use	(bbl)	-	14,100	18,720	
Fresh Water Make-Up Required	(bbl)	120,000	105,900	101,280	
Fresh Water Price	($/bbl)	0.15	0.15	0.15	
FRESH WATER SUPPLY COST	**($)**	**18,000**	**15,885**	**15,192**	
Fresh Water Make-Up Required	(bbl)	120,000	105,900	101,280	
Fresh Water Transportation Price	($/bbl/mile)	0.02	0.02	0.02	
Fresh Water Transportation Distance	(miles)	10	10	10	
FRESH WATER TRANSPORTATION COST	**($)**	**24,000**	**21,180**	**20,256**	
Flowback Volume	(bbl)	30,000	30,000	30,000	
Treatment Price	($/bbl)	-	1	3.5	
TREATMENT COST	**($)**	**-**	**30,000**	**105,000**	
Volume of Treated Water	(bbl)	-	14,100	18,720	
Treated Water Transportation Price	($/bbl/mile)	-	0.04	0.02	
Treated Water Transportation Distance	(miles)	-	10	50	
TREATED WATER TRANSPORTATION COST	**($)**	**-**	**5,640**	**18,720**	
Disposal Volume	(bbl)	30,000	15,900	11,280	
Disposal Transportation Price	($/bbl/mile)	0.04	0.04	0.04	
Disposal Transportation Distance	(miles)	450	450	450	
DISPOSAL TRANSPORTATION COST	**($)**	**540,000**	**286,200**	**203,040**	
Disposal Volume	(bbl)	30,000	15,900	11,280	
Injection Costs	($/bbl)	1	1	1	
DISPOSAL (INJECTION COST)	**($)**	**30,000**	**15,900**	**11,280**	
TOTAL WATER MANAGEMENT COST PER FRAC	**($)**	**612,000**	**374,805**	**373,488**	
			39%	**39%**	

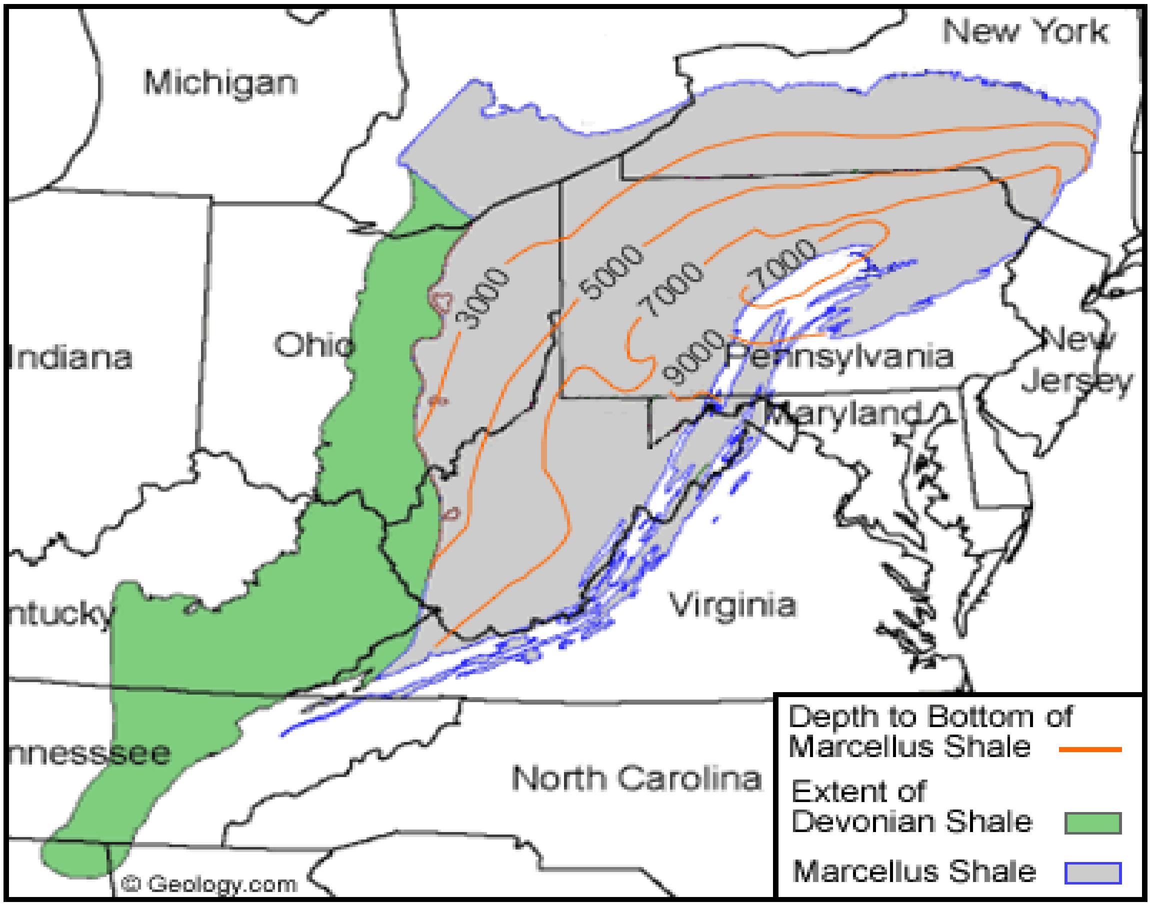
Conclusion and Recommendation

Finding the appropriate method of wastewater disposal after a hydraulic fracturing process is important to an operator because the process of injecting water into deep formations to release trapped natural gas is mainly dependent on the availability and management of water. Understanding what method of disposal will be appropriate for a specific operator could be dependent on many factors ranging from industry practice, operating culture, cost, risk management, and other elements that are important to an operator.

In my view, there is no specific right or wrong method as long as it meets the objectives of the operator and it protects the environment in a socially responsible manner. The major challenge to natural gas operators today is the issue of price and transportation. If the price of natural gas improves, operators will be willing to explore and drill which will provide the necessary incentives to invest in research and development that would improve wastewater disposal methods and technology. The issue of transportation of natural gas is also correlated to the subject of price since the advent of hydraulic fracturing technology has increase the quantity of reserves in the U.S, providing the network infrastructure to move the natural gas to necessary demand centers has been challenging. As the challenges of infrastructure get fixed so will the ability for natural gas operators to react to demand which will improve the price of natural gas.

From a political standpoint, the U.S government has a responsibility to stay ahead of the development in the natural gas industry to enable lawmakers to use laws and policies to ensure that operators in the U.S can produce responsibly while meeting the needs of the local economy and also compete in the global market.

Figure 2 - Depth to bottom of the Marcellus Shale

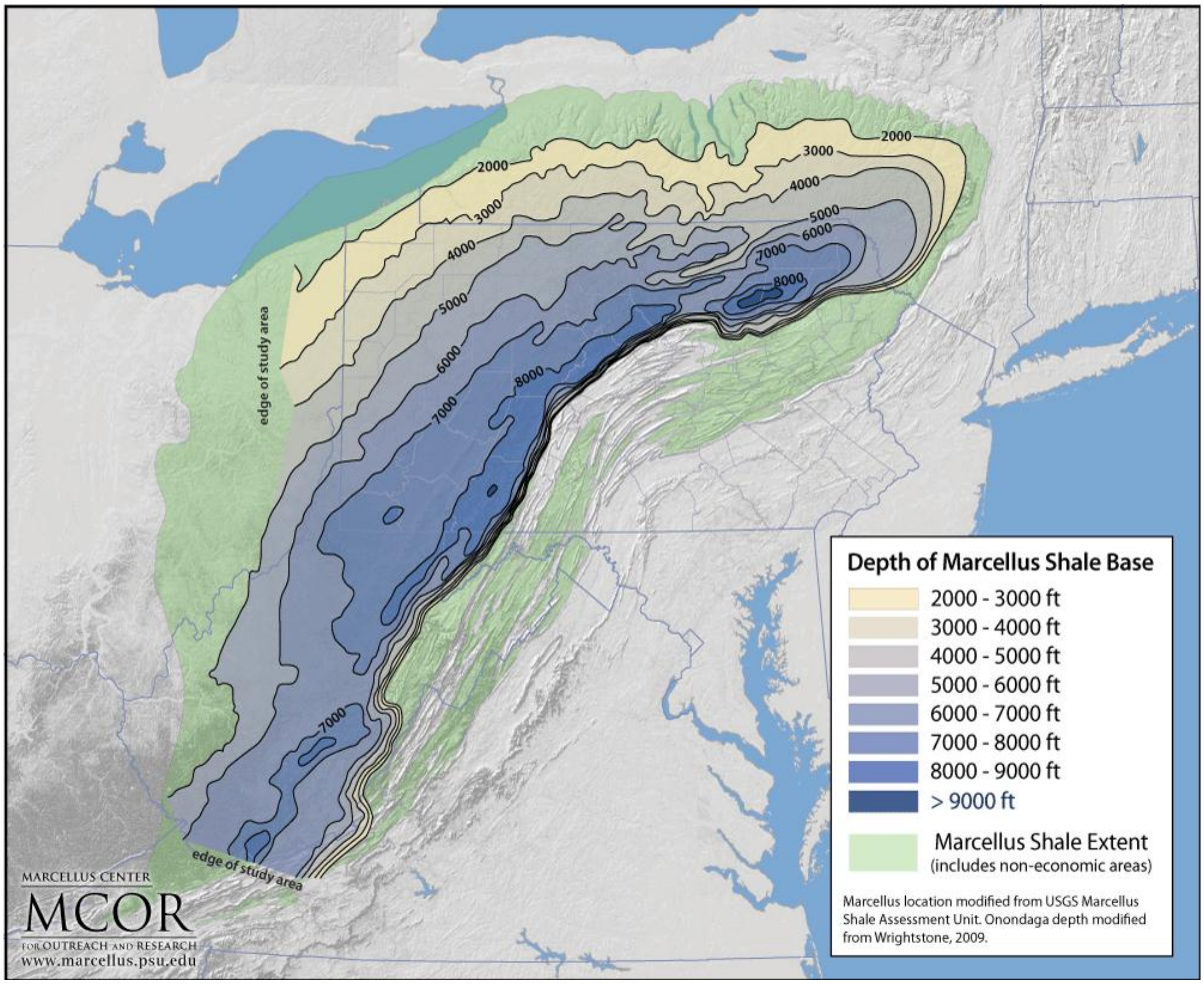


Source: http://geology.com/articles/marcellus-shale.shtml

Figure 3 - Historical Natural Gas Prices

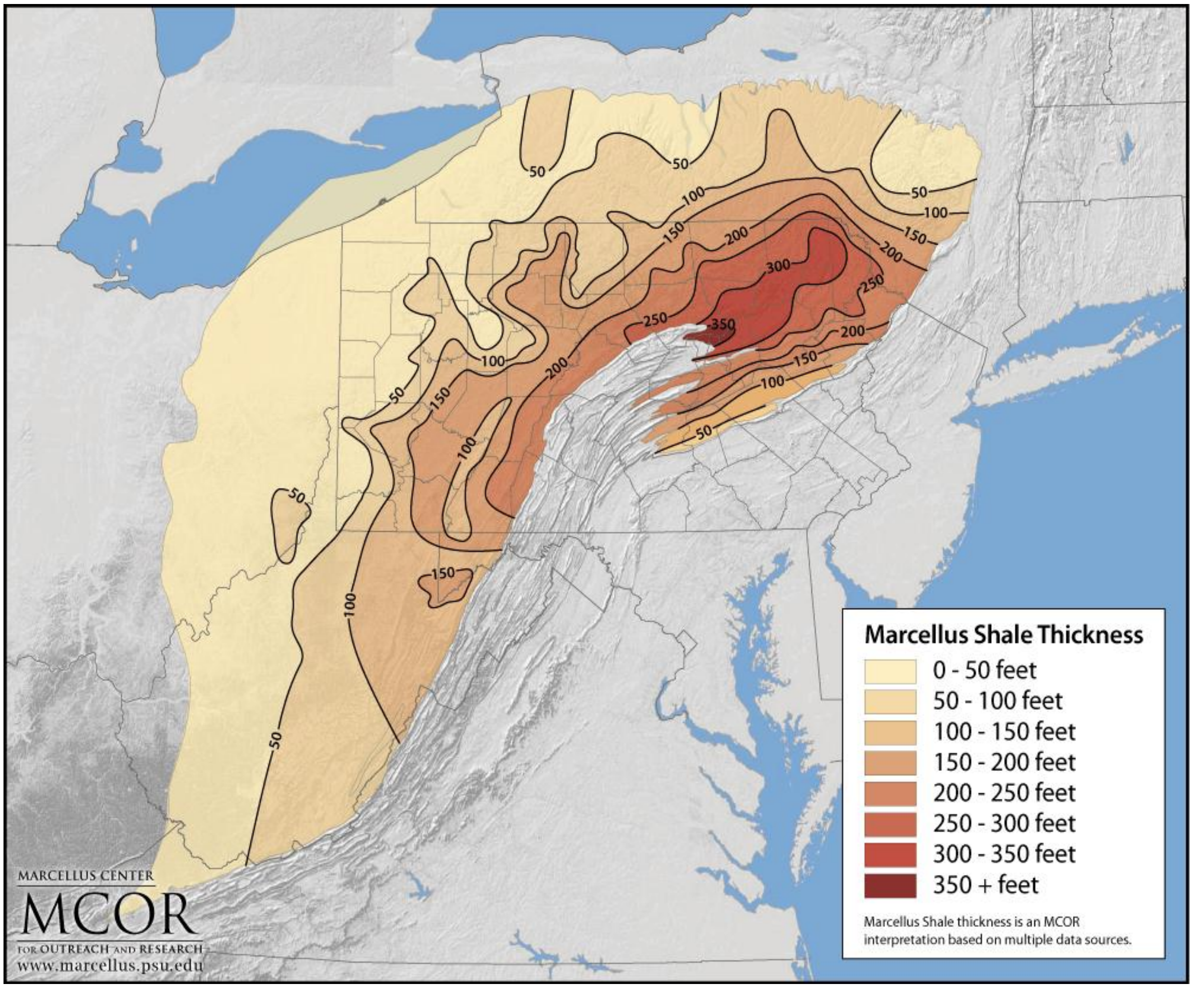
Source: Print Screen from Bloomberg by Junaid Yisa

Figure 4 - Depth of Marcellus Shale Basin



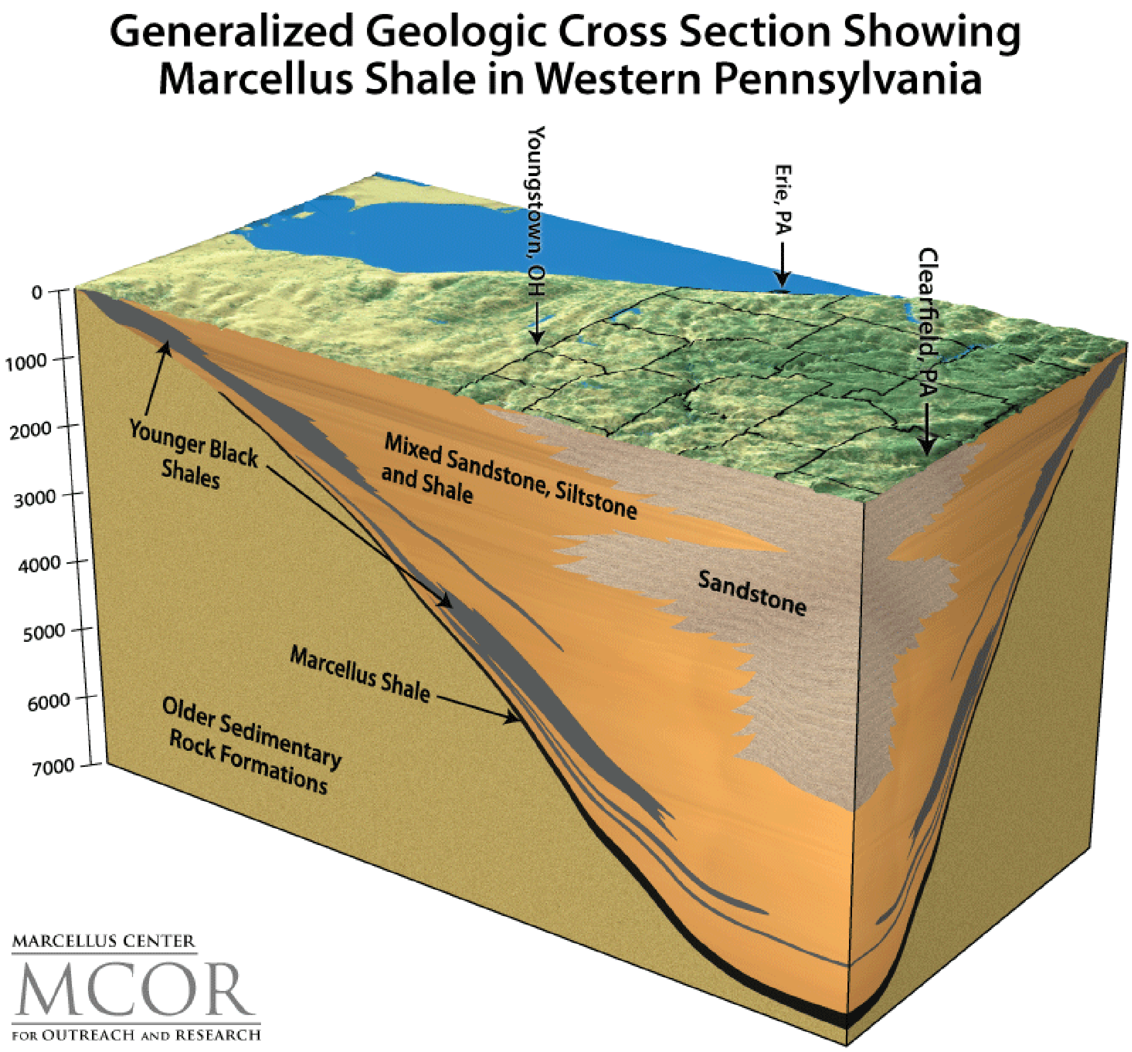
Source: http://www.marcellus.psu.edu/resources/maps.php

Figure 5 - Marcellus Shale Thickness



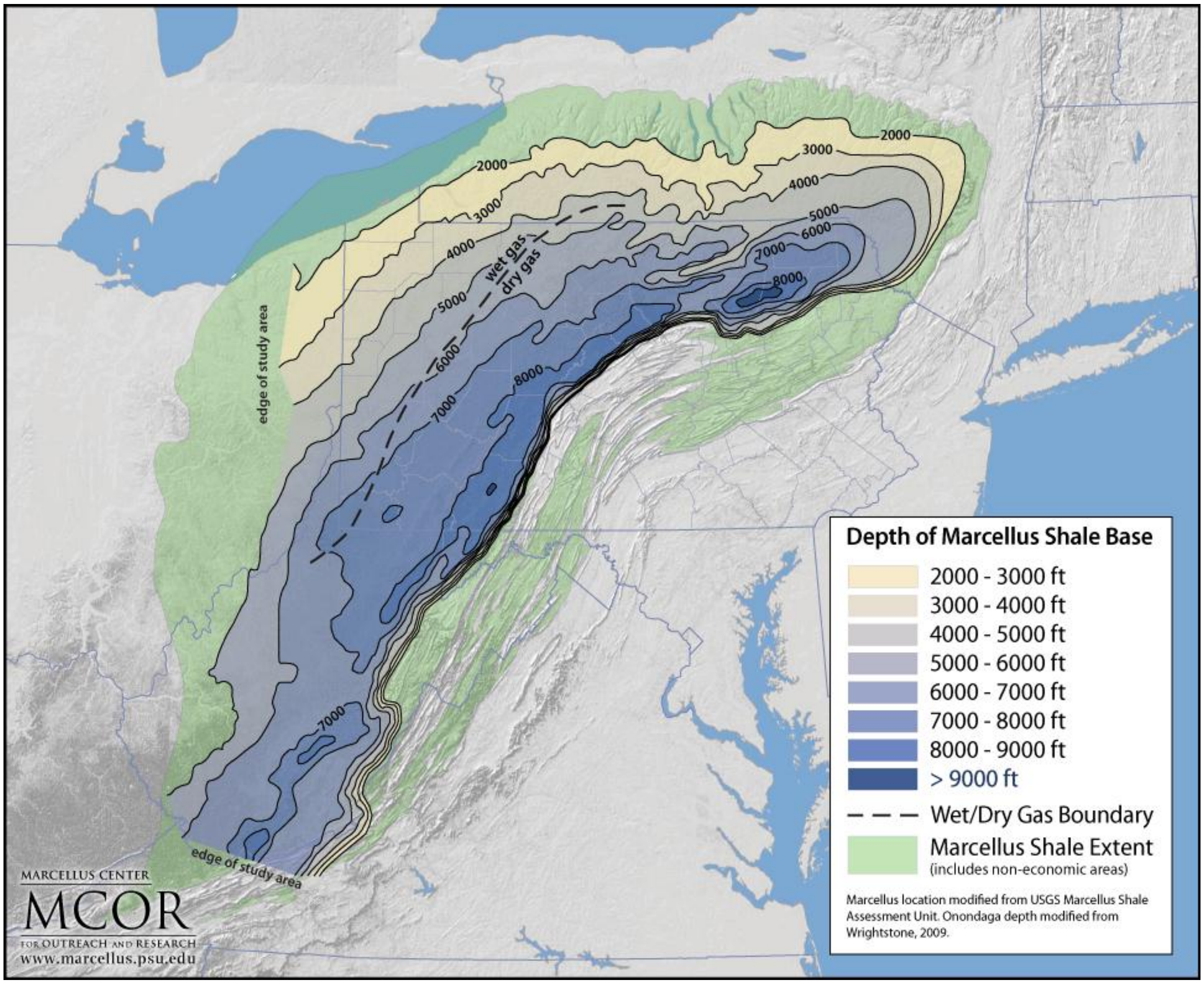
Source: http://www.marcellus.psu.edu/resources/maps.php

Figure 6 - Generalized Geologic Cross Section Showing Marcellus Shale in Western Pennsylvania



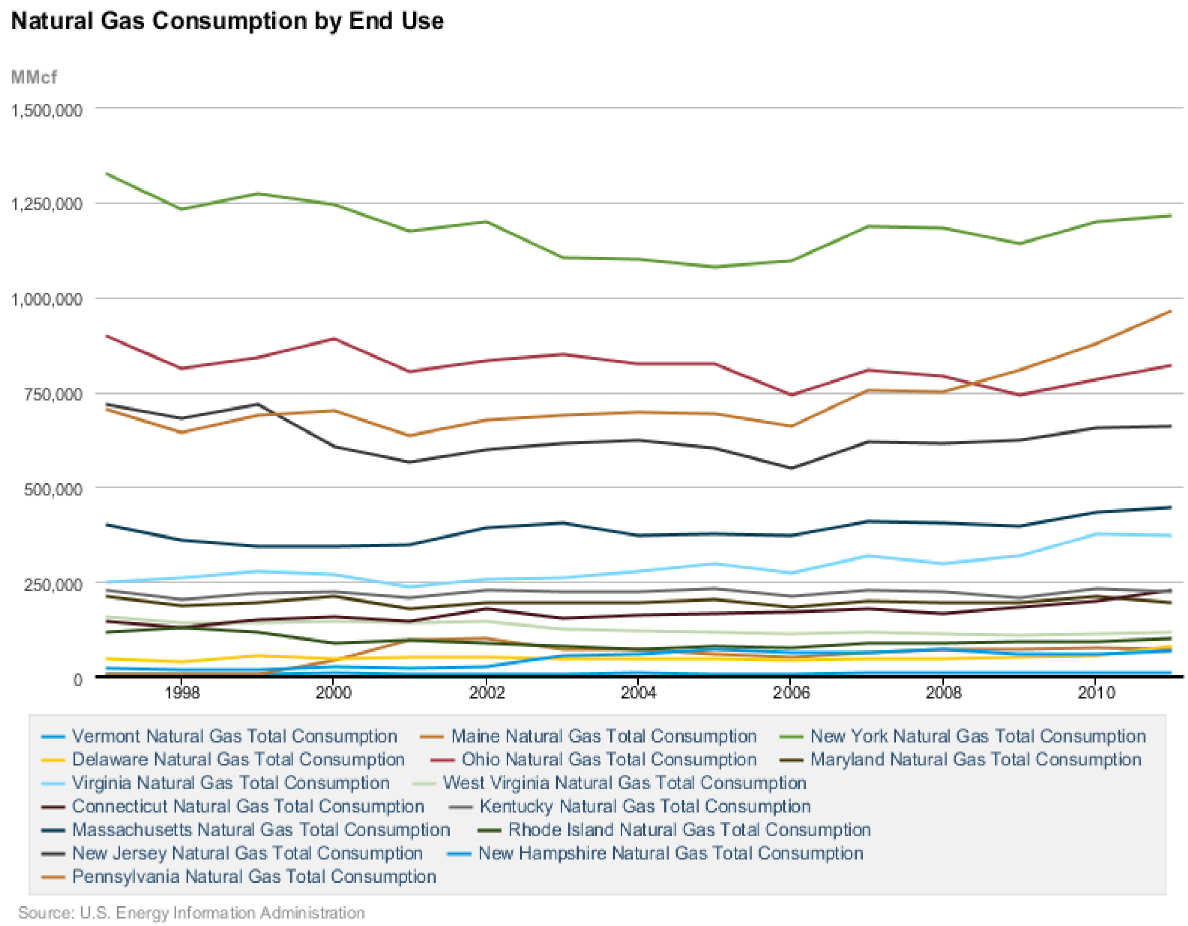
Source: http://www.marcellus.psu.edu/resources/maps.php

Figure 7 - Depth of the Marcellus Shale Basin/Wet & Dry Boundary



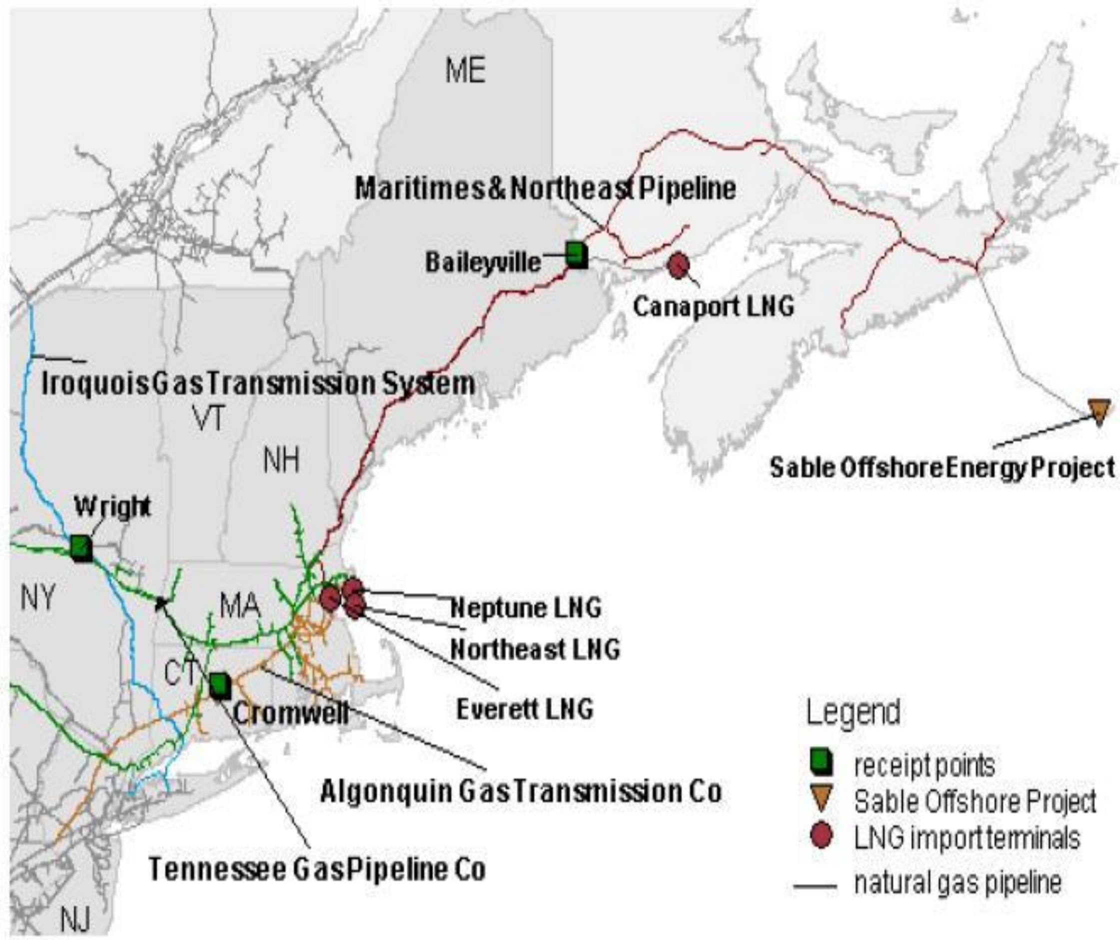
Source: http://www.marcellus.psu.edu/resources/maps.php

Figure 8 - Natural Gas Consumption by End Use



Source: http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm

Figure 9 - Natural Gas Pipeline Infrastructure in the Northeast



Source: http://blogs.constellation.com/energy4business/2013/01/25/northeast-gas-market-experiences-price-spikes-due-to-pipeline-constraints/

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